

$B \rightarrow X_s \tau^+ \tau^-$ in a CP spontaneously broken two Higgs doublet model

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The differential branching ratio, CP asymmetry and lepton polarization P_N for $B \rightarrow X_s \tau^+ \tau^-$ in a CP spontaneously broken two Higgs doublet model are computed. It is shown that contributions of neutral Higgs bosons to the decay are quite significant when $\tan \beta$ is large and P_N can reach five percent.

The origin of the CP violation has been one of main issues in high energy physics. The measurements of electric dipole moments of the neutron and electron and the matter-antimatter asymmetry in the universe indicate that one needs new sources of CP violation in addition to the CP violation come from CKM matrix, which has been one of motivations to search new theoretical models beyond the standard model (SM).

The minimal extension of the SM is to enlarge the Higgs sectors of the SM. It has been shown that if one adheres to the natural flavor conservation (NFC) in the Higgs sector, then a minimum of three Higgs doublets are necessary in order to have spontaneous CP violations ¹. However, the constraint can be evaded if one allows the real and image parts of $\phi_1^+ \phi_2$ have different self-couplings and adds a linear term of $\text{Re}(\phi_1^+ \phi_2)$ in the Higgs potential (see below Eq. (1)). Then, one can construct a CP spontaneously broken (and Z_2 -symmetry softly broken) two Higgs doublet (2HDM), which is the minimal among the extensions of the SM that provide new source of CP violation.

Rare decays $B \rightarrow X_s l^+ l^-$ ($l = e, \mu$) have been extensively investigated in both SM and the beyond ^{2,3}. The inclusive decay $B \rightarrow X_s \tau^+ \tau^-$ has also been investigated in the SM, the model II 2HDM and SUSY models with and without including the contributions of NHB ^{4,5}. In this note we investigate the inclusive decay $B \rightarrow X_s \tau^+ \tau^-$ with emphasis on CP violation effect in a CP spontaneously broken 2HDM in which the up-type quarks get masses from Yukawa couplings to the one Higgs doublet H_2 and down-type quarks and leptons get masses from Yukawa couplings to the another Higgs doublet H_1 . The contributions from exchanging neutral Higgs bosons now is enhanced roughly by a factor of $tg^2 \beta$ and can compete with those from exchanging γ , Z when $tg \beta$ is large enough. We shall be interested in the large $\tan \beta$ limit in this note.

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Consider two complex $Y = 1$ $SU(2)_w$ doublet scalar fields, ϕ_1 and ϕ_2 . The Higgs potential which spontaneously breaks $SU(2) \times U(1)$ down to $U(1)_{EM}$ can be written in the following form^{5,6}:

$$V(\phi_1, \phi_2) = \sum_{i=1,2} [m_i^2 \phi_i^+ \phi_i + \lambda_i (\phi_i^+ \phi_i)^2] + m_3^2 \text{Re}(\phi_1^+ \phi_2) + \lambda_3 [(\phi_1^+ \phi_1)(\phi_2^+ \phi_2)] + \lambda_4 [\text{Re}(\phi_1^+ \phi_2)]^2 + \lambda_5 [\text{Im}(\phi_1^+ \phi_2)]^2 \quad (1)$$

Hermiticity requires that all parameters are real so that the potential is CP conservative. It is easy to see that the minimum of the potential is at $\langle \phi_1 \rangle = v_1$ and $\langle \phi_2 \rangle = v_2 e^{i\xi}$, thus breaking $SU(2) \times U(1)$ down to $U(1)_{EM}$ and simultaneously breaking CP, as desired.

In the case of large $\tan \beta$, if we neglect all terms proportional to c_β and taken $s_\beta = 1$ in the mass-squared matrix of neutral Higgs, one would get that one of the Higgs boson mass is 0, obviously which is conflict with current experiments. So instead, below we will discuss a special case in which a analytical solution of the mass matrix can be obtained.

Assuming $4\lambda_1 c_\beta^2 = \lambda_4 - \lambda_5$ and neglecting other terms proportional to c_β in the mass-squared matrix, one obtains the masses of neutral Higgs bosons

$$m_{H_1^0}^2 = 2(\lambda_4 - \lambda_5)v^2 s_\psi^2, \quad m_{H_2^0}^2 = 2(\lambda_4 - \lambda_5)v^2 c_\psi^2, \quad m_{H_3^0}^2 = 4(\lambda_2 + \lambda_3)v^2 \quad (2)$$

with the mixing angle $\psi = \frac{\xi}{2}$.

Then it is straightforward to obtain the couplings of neutral Higgs to fermions

$$H_1^0 \bar{f}f : -\frac{igm_f}{2m_w c_\beta}(-s_{\xi/2} + ic_{\xi/2}\gamma_5); \quad H_2^0 \bar{f}f : -\frac{igm_f}{2m_w c_\beta}(c_{\xi/2} + is_{\xi/2}\gamma_5), \quad (3)$$

where f represents down-type quarks and leptons. The coupling of H_3^0 to f is not enhanced by $\tan \beta$ and will not be given explicitly. The couplings of the charged Higgs bosons to fermions are the same as those in the model II 2HDM. This is in contrary with the model III⁷ in which the couplings of the charged Higgs to fermions are quite different from model II. It is easy to see from Eq. (3) that the contributions come from exchanging NHB is proportional to $\sqrt{2}G_F s_{\xi/2} c_{\xi/2} m_f^2 / \cos^2 \beta$, so that we have the constraint $\sqrt{|\sin \xi|} \tan \beta < 50$ from the neutron EDM, and the constraint from the electron EDM is not stronger this. The constraints on $\tan \beta$ due to effects arising from the charged Higgs are the same as those in the model II and can be found in ref.^{8,4}.

The transition rate for $b \rightarrow s \tau^+ \tau^-$ can be computed in the framework of

the QCD corrected effective weak Hamiltonian

$$H_{eff} = \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left(\sum_{i=1}^{10} C_i(\mu) O_i(\mu) + \sum_{i=1}^{10} C_{Q_i}(\mu) Q_i(\mu) \right) \quad (4)$$

where $O_i (i = 1, \dots, 10)$ is the same as that given in the ref.², Q_i 's come from exchanging the neutral Higgs bosons and are defined in Ref.⁴.

The coefficients C_i 's at $\mu = m_W$ have been given in the ref.² and C_{Q_i} 's are (neglecting the $O(tg\beta)$ term)

$$\begin{aligned} C_{Q_1}(m_W) &= \frac{m_b m_\tau t g^2 \beta x_t}{2 \sin^2 \theta_W} \left\{ \sum_{i=H_1, H_2} \frac{A_i}{m_i^2} (f_1 B_i + f_2 E_i) \right\}, \\ C_{Q_2}(m_W) &= \frac{m_b m_\tau t g^2 \beta x_t}{2 \sin^2 \theta_W} \left\{ \sum_{i=H_1, H_2} \frac{D_i}{m_i^2} (f_1 B_i + f_2 E_i) \right\}, \\ C_{Q_3}(m_W) &= \frac{m_b e^2}{m_\tau g_s^2} (C_{Q_1}(m_W) + C_{Q_2}(m_W)), \\ C_{Q_4}(m_W) &= \frac{m_b e^2}{m_\tau g_s^2} (C_{Q_1}(m_W) - C_{Q_2}(m_W)), \\ C_{Q_i}(m_W) &= 0, \quad i = 5, \dots, 10 \end{aligned} \quad (5)$$

where

$$\begin{aligned} A_{H_1} &= -s_{\xi/2}, \quad D_{H_1} = i c_{\xi/2}, \quad A_{H_2} = c_{\xi/2}, \quad D_{H_2} = i s_{\xi/2}, \\ B_{H_1} &= \frac{i c_{\xi/2} - s_{\xi/2}}{2}, \quad B_{H_2} = \frac{c_{\xi/2} + i s_{\xi/2}}{2}, \\ E_{H_1} &= \frac{1}{2} (-s_{\xi/2} c_1 + c_{\xi/2} c_2), \quad E_{H_2} = \frac{1}{2} (c_{\xi/2} c_1 + s_{\xi/2} c_2) \\ c_1 &= -x_{H^\pm} + \frac{c_\xi}{2 s_{\xi/2}^2} x_{H_1} (c_\xi + i s_\xi) + \frac{1}{2 s_{\xi/2}^2} x_{H_1} \\ c_2 &= i [-x_{H^\pm} + \frac{c_{\xi/2} x_{H_1}}{s_{\xi/2}} (s_\xi - i c_\xi)]. \end{aligned} \quad (6)$$

The QCD corrections to coefficients C_i and C_{Q_i} can be incooperated in the standard way by using the renormalization group equations⁴. The explicit expressions of the invariant dilepton mass distribution, CP asymmetries A_{CP}^i ($i=1,2$) in branching ratio and in forward-backward (F-B) asymmetry and normal polarization of lepton P_N for $B \rightarrow X_s \tau^+ \tau^-$ can be found in ref.⁵.

The following parameters have been used in the numerical calculations: $m_t = 175 \text{ GeV}$, $m_b = 5.0 \text{ GeV}$, $m_c = 1.6 \text{ GeV}$, $m_\tau = 1.77 \text{ GeV}$, $\eta = 1.724$, $m_{H_1} = 100 \text{ GeV}$, $m_{H^\pm} = 200 \text{ GeV}$.

From the numerical results, the following conclusions can be drawn. A. The contributions of NHB to the differential branching ratio $d\Gamma/ds$ are significant when $\tan\beta$ is not smaller than 30 and the masses of NHB are in the reasonable region. For $\tan\beta=30$, $d\Gamma/ds$ is enhanced by a factor of 6 compared to SM. B. The direct CP violation in branching ratio A_{CP}^1 is of order 10^{-4} which is hard to be measured. C. The direct CP violation in F-B A_{CP}^2 can reach about a few percents and is strongly dependent of the CP violation phase ξ and comes mainly from exchanging NHBs, as expected. D. The CP-violating polarization P_N is also strongly dependent of the CP violation phase ξ and can be as large as 5% for some values of ξ , which should be within the luminosity reach of coming B factord comes mainly from NHB contributions in the most of range of ξ . So it is possible to discriminate the model from the other 2HDMs by measuring the CP-violated observables such as A_{CP}^2 , P_N if the nature chooses large $\tan\beta$.^b

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